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Experimental study on the effect of various parameters of recirculating flows induced by vane swirler

Bhavin K.Shah[1], Ashok K.Dhakiya[2], Arvind.S.Mohite[3]
[1,2,3]Department of mechanical engineering, Faculty of technology & engineering, M.S. University, Vadodara.

Abstract—Swirling flow generates rotating flows, turbulence and free jet wakes at the downstream of swirler in combustion chamber. The core objective of this study is to present the details of the experimental procedure and measurements made in an axisymmetric swirler model. The flow through 6 and 8 blades 45° vane swirler is studied experimentally. An overlap angle of 30° is provided between the vanes for the proper guidance of the flow through swirler. A hemi spherical bluff body is attached to the hub in order to overcome the inlet flow field distortion. A 6.5 mm diameter five-hole probe has been used. A traversing mechanism is used to control the traversing of the probe. The recirculation velocities at the centre core and corner regions are well captured with the five-hole probe. Five-hole pitot probe measurements along the entire length of the model at different stations, allow the determination of axial mean velocity component and pressure field parameters, which provide comprehensive information to aid and understand such complex recirculation flows. Flow field characteristics downstream of the swirler at different axial locations are examined in detail. The recirculation length and width are found to be strongly dependent on the amount of turbulence created by the vane swirler.

Keywords—Swirler, Adverse pressure gradient, Vane angle, Recirculation region, Five-hole probe.

I. INTRODUCTION

Swirl flows offer an interesting field of study for aerospace and mechanical engineers in general and for combustion engineers in particular since it involves complex interaction of recirculation and turbulent mixing which aid flame stabilization in combustion systems. gradient, this aids to form a central toroidal recirculation zone. Swirling flows, which are highly complex, have the characteristics of both rotating motion and free turbulence phenomenon encountered as in jets and wake flows. Swirling flows in both reacting and non-reacting conditions occur in a wide range of applications such as gas turbines, marine combustor, burners, chemical processing plants, rotary kilns and spray dryers. Swirling jets are used as a means of controlling flames in combustion chambers. The presence of swirl results in setting up of radial and axial pressure gradients, which in turn influence flow fields. In case of strong swirl the adverse axial pressure gradient is sufficiently large to result in reverse flow along the axis and the setting up of an internal circulation zone. The degree of swirl is usually characterized by means of a non dimensional number called the swirl number *S*, which is defined as the ratio of the axial flux of swirl momentum (*GØ*) divided by the axial flux of axial momentum (*Gx*) times the equivalent nozzle radius.

$$S = G\O / (Gx\, R)$$

However for vane swirlers, the tan (θ) alone may be taken as a measure of the degree of swirl where θ is the vane angle. Swirl flows can be classified into weak, medium and strong swirl based on the swirl number '*S*'. If swirl number is less than 0.3 it is usually classified as weak swirl and if it is between 0.3 and 0.6 it is called medium swirl and if the swirl number is greater than 0.6, it is called strong swirl. Swirling flows are highly three dimensional and it is quite complex to obtain enough details experimentally to fully understand it and to comprehend the mechanisms involved. Hence the basic objectives of the paper are: (i) to provide a systematic and experimental measurements of axial, radial and tangential velocity profiles downstream of the swirler in order to understand the flow field characteristics, (ii) to provide a base line experimental data for the validation of numerical results, and (iii) to understand the effect of turbulence and recirculation zone created by vane swirler.

II. BASIC GEOMETRY AND ITS PARTS

The swirler model with vane angle 45° is made in transparent, Perspex material as shown in Fig. 1. The geometry consists of an inlet pipe of length 350 mm, 120 mm outer diameter and hub diameter of 40 mm. The inlet pipe is provided with a 10mm hole to measure the mean velocity at the inlet with the help of a static pitot tube. The inlet pipe is followed by a conical diffuser with inlet dia. of 120 mm and 250 mm outlet dia. Diffuser is followed by sudden expansion round chamber of 250 × 250 mm cross-section and a length of 1100 mm. The holes of 10 mm dia. are drilled in diffuser and chamber to measure the velocity by five hole probe. A tail pipe of 120 mm diameter and length of 1300 mm is provided to prevent the atmospheric disturbances in the development of the flow. The swirler is placed in the inlet pipe with the vane tip made to coincide exactly with the outer plane of the inlet pipe as stated by Mathur and Macallum7.

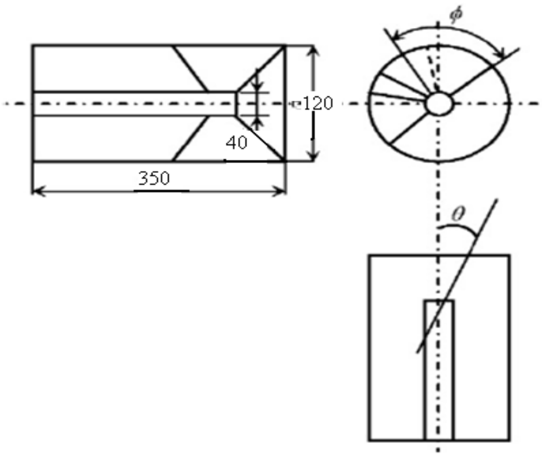

Fig.1 swirler portion geometry

III. EXPERIMENTAL PROCEDURE

Design Details of 45° Annular Vane Swirler

The design of vane swirler is based on Mathur and Macullum1. The design of 45° vane swirler is shown in Fig. 2. There are eight vanes 2 mm in thick. The vanes are symmetrical, and the trailing edges of the vanes do not lie in the plane of the hub exit. The angle subtended by a vane at the axis, when viewed in the axial direction is 75°, giving an overlap of 30° between adjacent vanes. The length of the hub is 175 mm and a hemispherical bluff body is attached upstream of the hub in order to smoothly guide the fluid particle circumferentially, impinging on the hub.

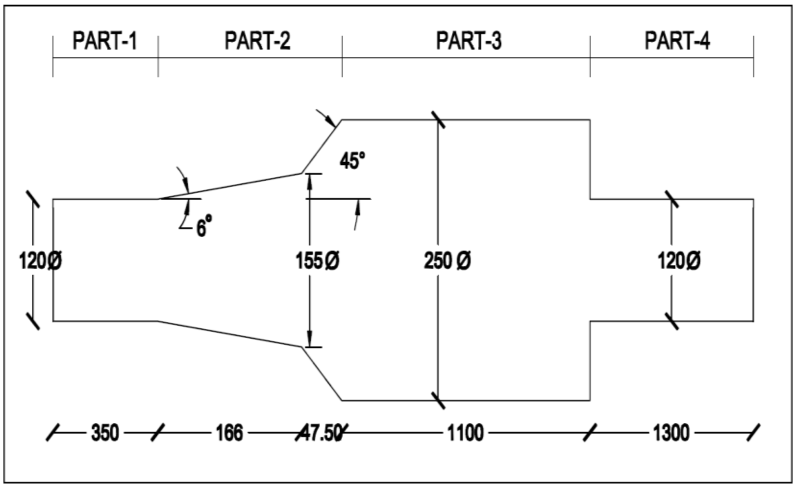

Fig.2 geometry of combustion swirler set-up

IV. EXPERIMENTAL SET UP WITH TEST FACILITY

Experiments have been carried out in a low speed vane blower with cascade tunnel test facility. Blower is used to provide the flow of air through combustion swirler set up. Blower has a backward flow type of vanes. Cascade wind tunnel is of 75*75*60 in the cross section and placed at the exit of the blower with the help of convergent type of nozzle and small pipe. In wind tunnel the condition of the flow is of stagnation type. The three-dimensional swirler geometry is made from transparent Perspex material and it consists of an inlet pipe of length 350 mm, outer diameter 120 mm and hub diameter of 40 mm. The inlet pipe is attached to the wind tunnel as shown in Fig. 3. The vane swirler is placed in the inlet pipe with vane tip made to coincide with the exit plane of the inlet pipe. The inlet pipe is followed by a sudden expansion chamber of 250 × 250 mm round cross section of length 1100 mm. Holes of 10 mm diameter are drilled downstream of the swirler at various stations (A to P) in diffuser and chamber. The round chamber is followed by a tail end pipe of length 1300 mm and diameter of 120 mm. As already mentioned, the tail end pipe is provided to prevent the back flow of fluid affecting the swirl flow development in the round chamber. Based on the axial velocity profile at the inlet of the test section the bulk mean velocity is found to be 20 m/s for free jet. Table 1 gives the non-dimensional position of the measuring locations with respect to the axial length of the swirler downstream region, considering the exit of the swirler as the reference location to measure the positive X values as shown in fig. 3.

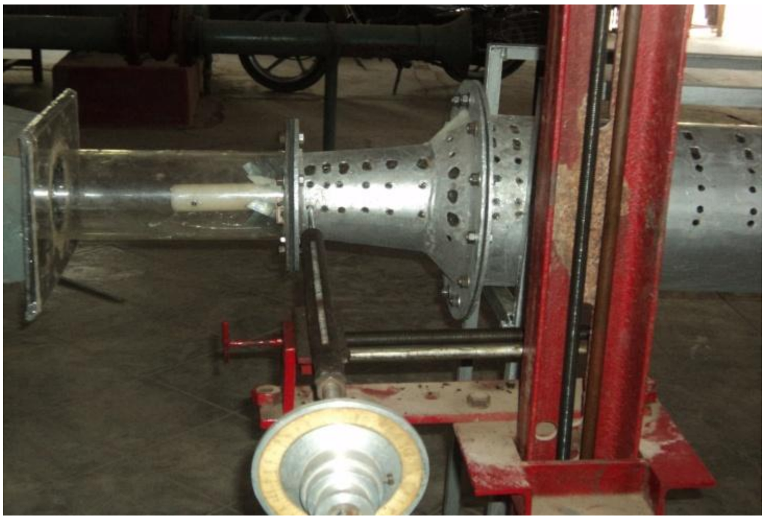

Fig.3 Experimental set up with five hole probe measurement procedure

V. PROBE CALIBRATION

The present experiment is related with the axial, tangential and radial velocity of the flow. So here five hole probe as shown in fig.4 is used to find out these velocity components. For this, the calibration of five hole probe is done and then it is used for the experiment. The five hole probe was calibrated in a separated fabricated calibration section of 150cm x 220cm attached at the end of blower shown in fig.5. It was the probe was calibrated against a standard Pitot tube for dynamic pressure and pitch angle. Pressure signals from the Pitot tube and five tubes of the probe were read on multi tube manometer. Tunnel flow velocity was varied in steps and for each velocity readings of true dynamic pressure from standard pitot tube and the pressure of each tube of the probe after null position of side tube were recorded. These were repeated for pitch angle which was varied from -20^o to -20^o in steps of 5^o. The total pressure is then read directly from the centre tube when the pressure of side tubes is equal.

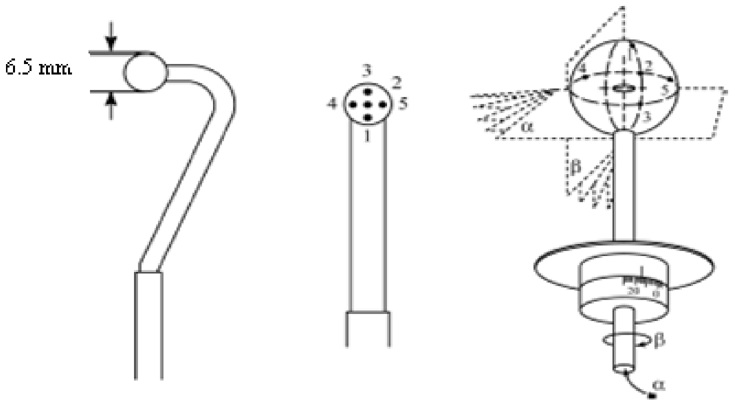

Fig.4 details of five hole probe

Fig.5 overview of calibration procedure

VI. CALIBRATION FOR DYNAMIC PRESSURE AND PITCH ANGLE

Fig.6 represent the graph of probe for dynamic head constant in which from different pitch angle from -20 to +20 deg. The different values of true dynamic head and probe head were plotted. After plotting all the values, average tread line is derived which give the value of dynamic head constant K = 2.32.

The graph for pitch angle constant represented in the fig. 3.7 in which at different pitch angle the value of (P_3- P_1) / (P_5- $P_{1\text{-}4}$) plotted and get average value of pitch angle constant which comes C = 8.72.

The instrument used for measuring velocities at various stations is the five-hole probe with a spherical diameter of 6.5 mm. The details of the probe are shown in Fig.5. The sensing head is a cobra shaped to allow probe shaft rotation without altering the probe tip rotation. The spherical head is turned in its guide about its axis until the pressures on the apertures 4 and 5 are equal and the torsional angle β can be read off the dial on the fixed marker. The readings in the pressure transmitter's *p1, p2, p3* and *p4* are noted down. The calibration curve is used to get the remaining properties such as the angle of flow and speed of flow $\bar{U}$, with all the components of velocity (Eqs (1)-(4)) with the pressure values measured from the above. The traversing mechanism is employed for linear traversing. Measurements of axial, radial and tangential components of velocities are obtained for every 10 mm radial distance at various X/D axial stations downstream of the swirler. A total of 16 axial locations downstream of the swirler axially are considered for the measurement,

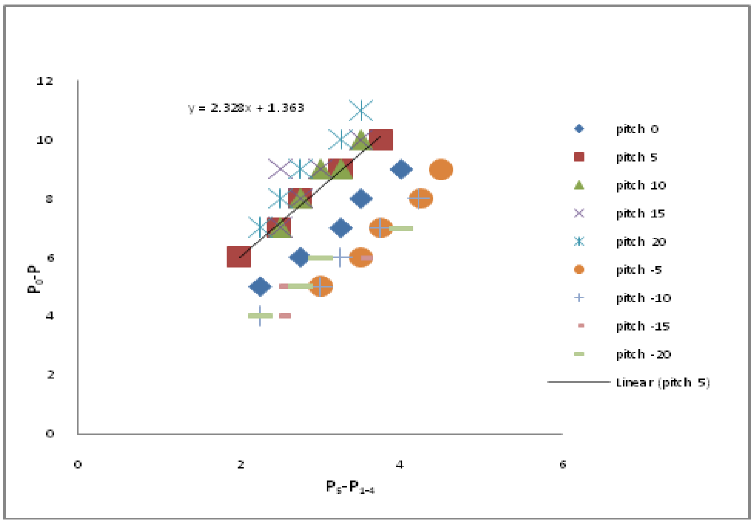

Fig.6 calibration of probe for dynamic head constant

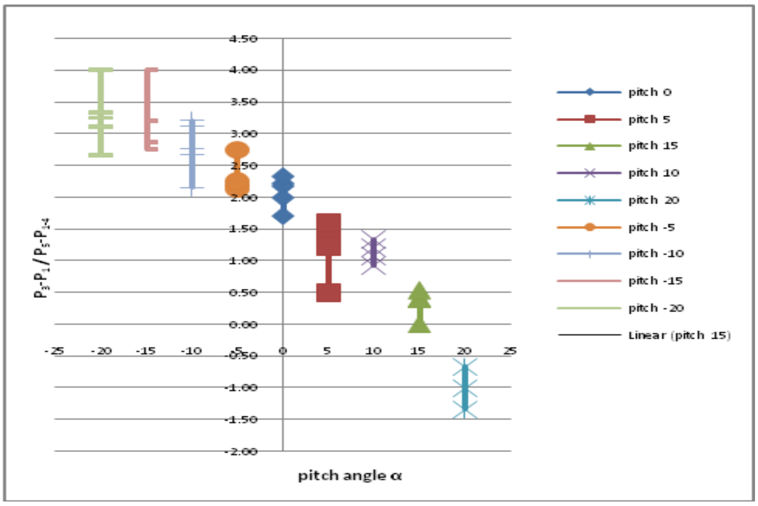

Fig.7 Calibration of probe for Pitch Angle Constant

$$\bar{U} = \frac{\sqrt{2(p_2 - p_4)}}{\rho K_{24}}$$

$$U = \bar{U} \cos\beta \cos\alpha$$

$$V = \bar{U} \sin\alpha$$

$$W = \bar{U} \cos\alpha \sin\beta$$

Where *U, V* and *W* are the axial, radial and tangential components of velocity *U* , *k24* is the constant obtained from calibration curve, *p1, p2, p3* and *p4* are the static pressures at respective holes and r is the density of air.

VII. PRESSURE LOSS FACTOR

The pressure loss factor is a measure of the flow resistance imparted to the air stream when it passes through the vane swirler. This pressure loss should be as small as possible for better fuel consumption in a combustion system. It is evident that the introduction of the vane swirlers necessarily introduces a certain amount of pressure loss in the system. The swirlers of varying vane angle are optimized when the pressure loss factor of each is known. The minimization of the total pressure drop is necessary in order to have proper recirculation zone for flame stabilization and sufficient turbulence and mixing. Total pressure loss factor (PLF) is a dimension less number and is defined as

$$\text{Pressure loss factor (PLF)} = \frac{P_{02} - P_{01}}{0.5\rho U_0^2}$$

Where the inlet stagnation pressure (P_{O1}) is measured in the inlet pipe upstream of the swirler and exit stagnation pressure (P_{O2}) is obtained at the exit of the expansion chamber and leaving to the atmosphere, ρ is density of the fluid in kg/m^3 and U_O is mean bulk inlet velocity to swirler (m/s).

VIII. RESULT AND DISCUSSIONS

The axial, radial and tangential velocities are measured at various axial locations. At each axial location the five-hole pitot sphere is moved for measuring the various velocity components. The fig.9 and fig.10 shows the axial velocity profiles from experimental values foe eight and six vanes swirlers respectively. At station A in fig.9, it is found that the negative velocity exists only at the centre point which is mainly due to the presence of hub and the axial velocity increases gradually as we move from the centre to 20 mm for eight vanes swirler and 15 mm for six vanes swirler radially and thereafter the velocity reduces and almost reaches a constant value near the wall. The increase in the axial velocity is due to impart of kinetic energy to the moving fluid by the vane swirler.

For eight vanes swirler, reverse velocity occurs from station A to station M and maximum reverse velocity occurs is of 4.92 m/s at station J in the central portion. While for six vanes swirler, reverse velocity occurs from station A to K and maximum reverse velocity occurs is of 4.68 m/s at station F in the central portion. It can also be seen from the profiles that the values of axial velocities are positive from station N to P for eight vanes swirler and from station L to P for six vanes swirler. The radial velocity, which is very small and negligible as compared to the axial and tangential aids in flame stabilization by providing a hot flow of recirculated combustion products and a reduced velocity region. The flame speed and flow velocity is matched in the recirculation zone. A good mixing of the reactants with air occurs due to the high turbulence generated by high shear stresses.

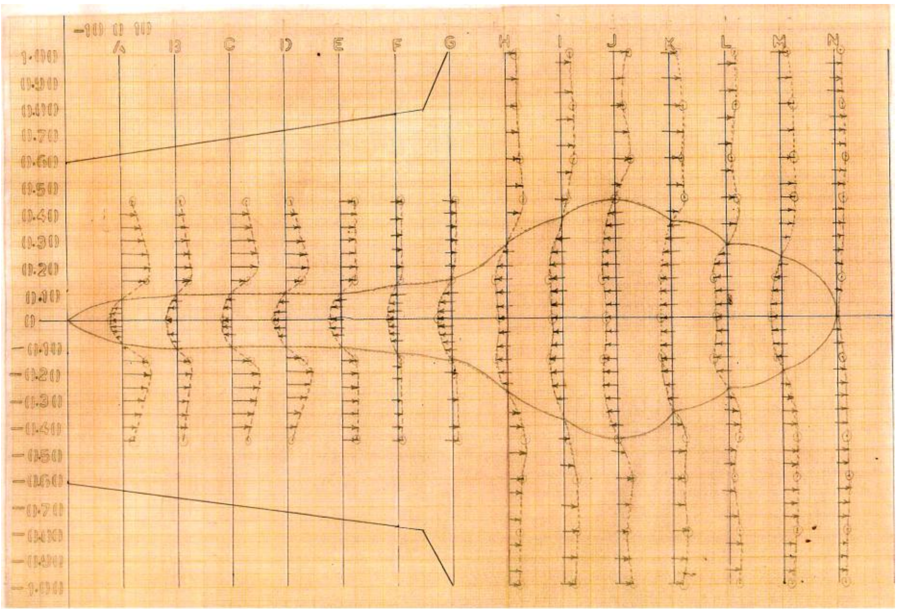

Fig.9 Recirculation zone for 45° 8 vanes swirler

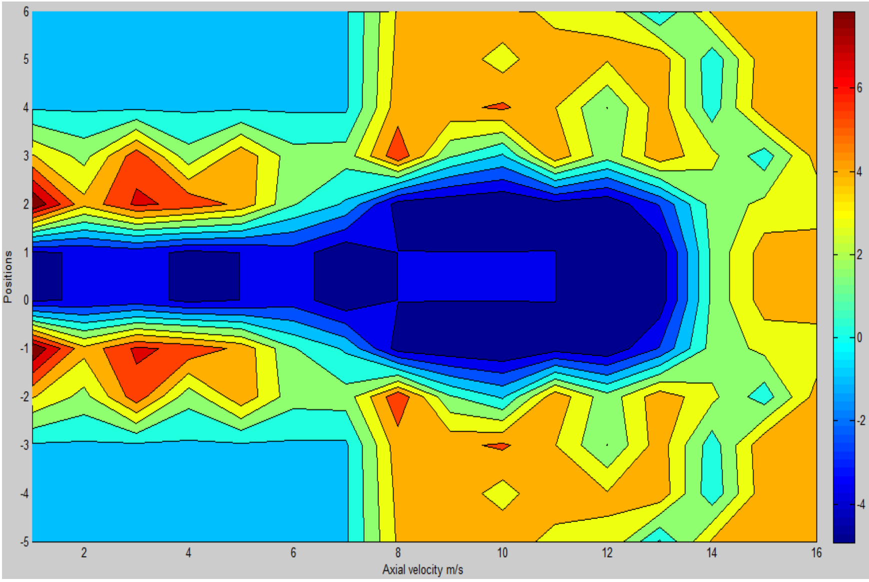

Fig.10 Recirculation zone for 45° 8 vanes swirler (MATLAB)

The boundary of the recirculation eddy is determined by the radial points at which the forward mass flow equals the reverse mass flow at the axial stations. A torroidal vortex may be formed within the recirculation zone, which is sustained by the momentum exchange into the main stream. The region which is enclosed where the axial velocity reaches zero magnitude in each axial plane is connected to obtain the recirculation region. This recirculation zone encloses a large torroidal vortex reverse flow situated in the centre of the jet. It is found to produce highly stable flames and also enables matching of zones of high turbulence intensity with those of high fuel concentration, resulting in higher combustion efficiency. From fig.9 it can be seen that the central recirculation occurs up to the station M and ends at station N in eight blade swirler case while for six vanes swirler case the central recirculation occurs up to the station K and ends at station L. From the recirculation zone for eight vanes swirler axial velocity, the recirculation expands rapidly and width of the liner of the recirculation becomes maximum nearer about 45 mm at station J in the radial direction from the central axis. The result shows that the width of the liner is maximum about 0.75D at the station J and the length of the recirculation is about 4.34D. In case of six vanes swirler as shown in fig.10, the maximum width of the recirculation zone is 35 mm at plane I on the either side of the central axis. Width of the liner is maximum about 0.59D and length of recirculation zone is 3.34D.

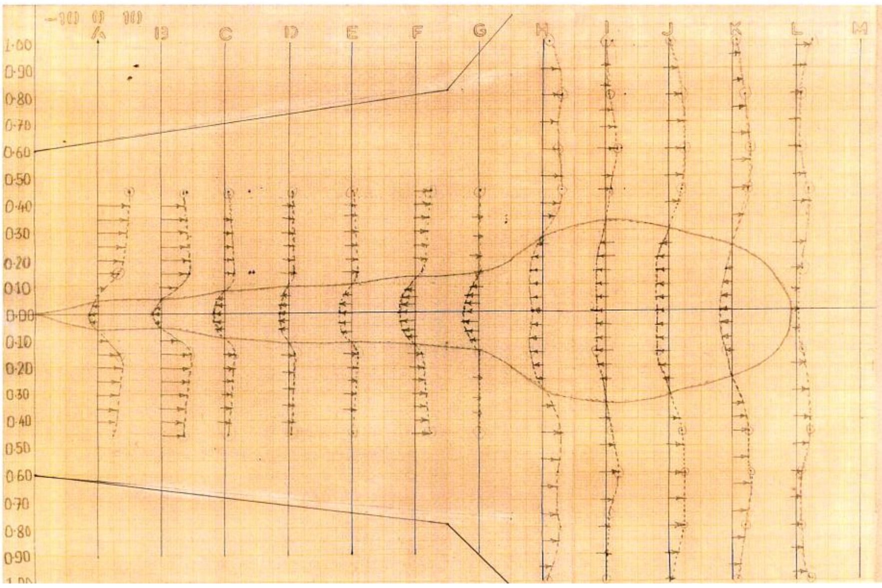

Fig.11 Recirculation zone for 45° 6 vanes swirler

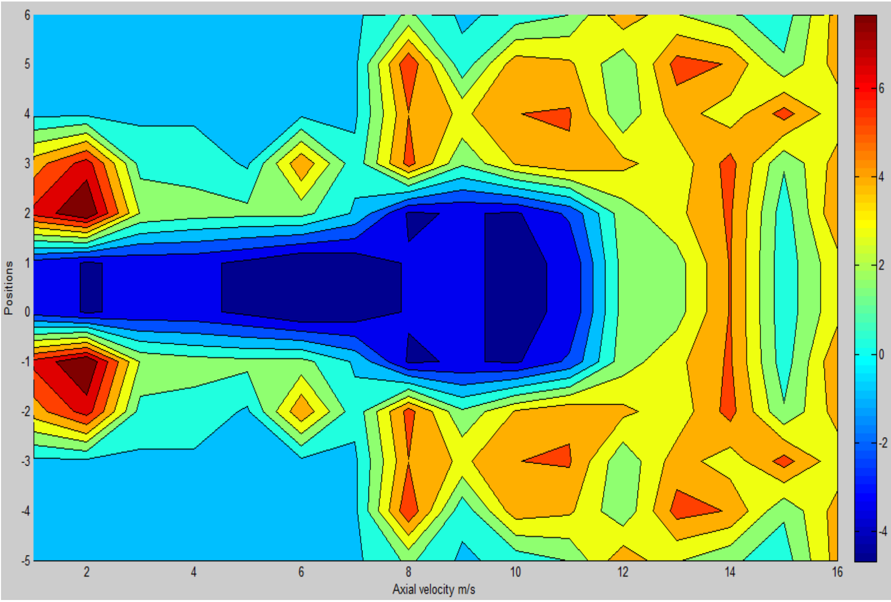

Fig.12 Recirculation zone for 45° 6 vanes swirler (MATLAB)

IX. CONCLUDING REMARKS

The experimental results provide a basic bench mark data for validating the numerical results. A 45° 8 vane swirler provides a reasonably good recirculation zone as compared to 6 vane swirler which may help flame stabilization more efficiently. The pressure loss factor is less for the 8 vane swirler. The tailpipe provided at the downstream of the swirler will drop the pressure loss by avoiding the atmospheric disturbance. The measurement of axial, radial and tangential velocity helps to determine the mean flow field characteristics downstream of the swirler, which can be used for reacting flow studies in burners and combustors.

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